Reverberation time, diffuse reflection, Sabine, and computerized prediction - part I.

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0. Introduction

This is the first part of a two-part on-line paper discussing reverberation time estimation with special emphasis on the effects of diffuse reflection in computerized prediction (CP) in relation to classical Sabine methods. The purpose of this paper is to discuss problems, pitfalls and techniques regarding reverberation time (RT) prediction and gives examples from idealized as well as actual rooms encountered in consulting practice. Reverberation time is far from the only measure a CP program can estimate and many further types of analysis are possible. However, the RT is a good starting point since it remains a central parameter in all applications of room acoustics and most acousticians would agree that *an appropriate RT is a necessary if not a sufficient condition for good room acoustics*. Part of what will be discussed here can also be found in a JAES article [Dalenbäck-94] and an IOA conference paper [Dalenbäck-95]. All CP examples shown are created using *CATT-Acoustic*™ v7.2.

Part I addresses:

1. **What effect has diffuse reflection on the RT?**
2. **Will diffuse reflection always affect the RT?**
3. **What effect has diffuse reflection on Sabine RT estimates?**
4. **Will not formulas such as Fitzroy and Arau-Puchades solve the problem?**

Part II will address:

1. Does diffuse reflection have to taken into account?
2. How can diffuse reflection be handled in a CP program?
3. Must diffuse reflection be handled with frequency dependence?
4. How can scattering coefficients be estimated?
5. How will diffuse reflection affect auralization?

1. What effect has diffuse reflection on the RT?

Diffuse reflection basically affects the RT in two ways, both in the decreasing direction:

1.1 Diffuse reflection forces surfaces to be more evenly utilized

By redirecting the reflected sound in many directions, diffuse reflection will let room surfaces be hit by sound in a

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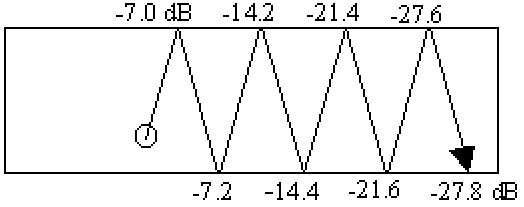
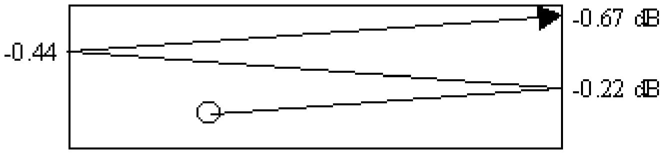
more uniform manner and absorbing surfaces will be better utilized. It thus prevents cases where the sound field e.g. becomes predominantly horizontal such as with hard parallel walls where a ceiling absorber does not have any major effect on the late decay. Clear examples of such cases are swimming and sports halls that often are rectangular and where the absorption for practical reasons is placed mainly in the ceiling and perhaps at upper wall parts. Another example is a reverberation chamber where the placement of an absorber (to be measured) on the floor requires the use of diffusing elements to give a good estimate of the random incidence absorption coefficient. Signs of the non-diffuse field in such rooms are double-sloped or otherwise non-linear (when expressed in dB) decay curves. This non-linearity is created because the sound in some direction (often the vertical) is quickly absorbed giving a fast initial decay (both due to the higher average absorption in the vertical direction and because vertical reflections occur more frequently - the height is often the smallest dimension). In contrast, the horizontal sound lingers since it is reflected between hard surfaces (and is also reflected less often), and thereby gives a slow late decay, see Figure I-1.



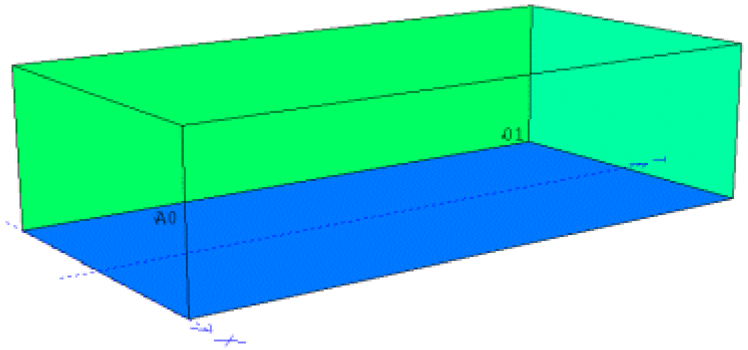
a) vertically reflected sound



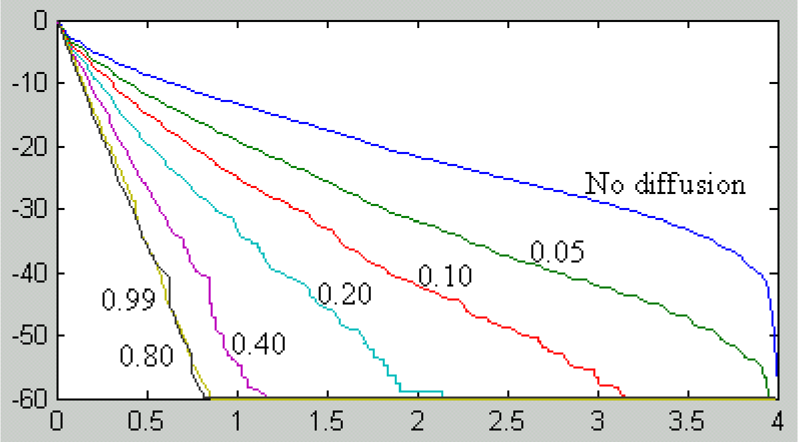
b) horizontally reflected sound

Figure I-1 Schematic illustration of vertically and horizontally reflected sound in a rectangular room with a ceiling absorber (alpha = 0.80) and hard walls and floor (alpha = 0.05) assuming no diffuse reflection. Reflection traces are those occurring within the same time period (i.e. total length of rays are roughly equal). Numbers indicated are the remaining relative levels after each reflection (for example, 10 log(1-0.80) = -7.0 dB and 10 log(1-0.05) = -0.22 dB).

The figure illustrates that - during the same time period - a vertical ray is attenuated by almost 30 dB due to absorption while the horizontal ray - in comparison - is hardly attenuated at all. With double-sloped decays the whole concept of an RT becomes ambiguous, especially if the *knee* of the decay is located inside the -5 to -35 dB span commonly used to evaluate RT (T-30). Figure I-2 illustrates the effects on the RT for scattering coefficients from 0 to 0.99 using an idealized rectangular room with an absorbing floor.



a) room model 24m x 12m x 6m.



b) decay curves using various wall scattering coefficients.

Figure I-2 Idealized room with 0.80 ceiling absorption and 0.05 on remaining surfaces. The Sabine RT is 1.04 sec and the Eyring RT is 0.90, predicted T-30 for a scattering coefficient of 0.99 is 0.85 sec. The RT values for degrees of diffusion can roughly be read off the time axis since the decay shown is 60 dB.

In this example the mean absorption is 0.26 so with high scattering coefficients (> 0.40) T-30 is very close to what the Eyring formula predicts (rather than Sabine since it assumes a lower mean absorption). Of course, if a rectangular room with uneven absorption actually *has* very smooth surfaces there *is* very little diffusion and the decay *will* be double-sloped. However, as can be seen in Fig. I-2, the scattering coefficient should never be set to zero (unless the purpose is to test a room's sensitivity to diffuse reflection) since, if nothing else, there are wall impedance mismatches and edge diffraction so it is quite clear that with zero scattering coefficients, or if diffusion is not handled at all, the estimated RT may be much too long. The example illustrates the extreme dependence on diffuse reflection in some cases and that the assigned scattering coefficients then must be estimated more carefully. This estimation is a difficult task but experience from using frequency dependent diffuse reflection for 10 years in a CP program (*CATT-Acoustic*^{TM}) has shown that with some basic guidelines, to be given in Part II, very good RT estimates can be obtained also in "non-Sabine" rooms.

1.2 Diffusers introduce absorption of their own

Diffusers also affect the RT by their own absorption, especially noticeable if a hard flat surface is replaced by a diffuser. This effect will not be further discussed and it is rather to be seen as the task of diffuser manufacturers to optimize their designs to give low-absorbing but high-diffusing alternatives where such are required or to offer particular combinations of absorbing and diffusing properties useful for specific purposes.

2. Will diffuse reflection always decrease the RT?

No, not always (but it may of course alter many other subjectively important parameters):

2.1 No, not with a "mixing" room shape

If the overall room shape and sizes and orientations of surfaces are such that they will cause reflections to be well "mixed" for purely geometrical reasons a diffuse field may be created even if no rough or diffusing surfaces are used. The introduction of diffusing surfaces will change the room responses even for a mixing room shape in many psycho-acoustically significant ways, but they may not alter the RT much.

2.2 No, not if the absorption distribution is even

In addition to diffuse reflection, the two major parameters determining the RT are the mean free path (*mfp*) and the mean absorption coefficient. The *mfp* is little dependent on room shapes and scattering coefficients and the classical value of $4V/S$ is a very good estimate. This means that with an even absorption distribution (i.e. all surfaces having similar absorption values within each octave-band) the actual RT is often very close to the classical Sabine (or Eyring if the mean absorption is higher). However, as soon as there is an audience in a room there is bound to be an uneven distribution, especially at high frequencies (wooden walls say 0.05 and audience say 0.80 as used in examples here) while at low frequencies the values are more similar (wooden walls say 0.15 and audience say 0.35). From these two cases it can be seen that *the most sensitive case is a non-mixing shape with uneven absorption* where the actual measured T-30 sometimes may be 2-3 times longer than that predicted by Sabine. Figure I-3 illustrates this case by using an actual sports hall.

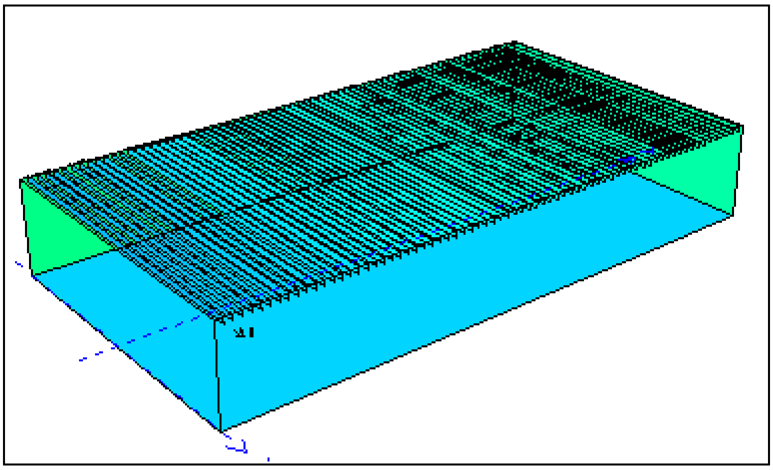


Figure I-3 Sports hall 43m x 23m x 7m. RT @ 1 kHz according to Sabine was 1.9 sec while the actually measured T-30 was 5.7 sec.

Sports hall project background: The acoustic consultant involved (Akustikon, Sweden) recommended to place class A absorbers between every second beam pair in the ceiling (ca. 50% coverage giving an effective ceiling absorption coefficient of 0.43 @ 1 kHz) and additional high absorption on at least one end wall and one side wall. However, to save money the contractor instead chose to use *only* the ceiling absorption and leave the rest basically as concrete (and it had later to be corrected - but that is another story). With only the ceiling used for absorption the calculated Sabine RT @ 1 kHz was 1.9 sec but when the RT was actually measured it was 5.7 sec. This is a clear case of a non-mixing shape with uneven absorption and this sports hall will be used again in Part II to show that the actual RT can be well predicted by selecting proper scattering coefficients, as was also done by the consultant. Note that this case is also affected by uncertainties regarding absorption coefficient values (further discussed in Part II) but any such uncertainties would result in a much smaller error than that caused by using the Sabine formula.

The sports hall is an extreme case but there are numerous cases that have similar, if not so extreme, properties. Concert halls and auditoria have one dominating absorbing surface (the audience but it is also - luckily - diffusing) while remaining surfaces are for the most part reflective and it is not uncommon with fairly rectangular shapes or large parallel side walls. Classrooms are other examples of non-mixing room shapes where a dedicated absorber often is placed in the ceiling while remaining surfaces are fairly hard (desks and chairs will have a diffusing effect but often not sufficient to completely prevent a non-linear decay). It should be mentioned that halls sometimes are *deliberately* designed to have a short early decay time and long late reverberation (e.g. by the use of reverberation chambers or otherwise coupled volumes) but that is quite different from making a faulty prediction of the expected RT in a room not realized to have a double-sloped decay.

3. What effect has diffuse reflection on Sabine RT estimates?

As indicated above the Sabine and Eyring equations both assume that reflections are fully diffuse and that each surface is visible from all other surfaces so that the utilization of the absorption of a surface can be considered to be in direct proportion to its relative area. This means that the classical equations *cannot be expected* to give good estimates unless a large fraction of the room surfaces are diffusing or if the room shape is mixing.

4. Will not formulas such as Fitzroy and Arau-Puchades solve the problem?

Alternate RT equations is the topic of a large number of journal articles and conference papers, many of which attempt to find a catch-all equation for RT estimation. Two such attempts to improve on the classical Sabine or Eyring formulas are those of [Fitzroy-59] and [Arau-Puchades-88]. These two formulas give a better estimate than the classical formulas in *some cases* but here a central question is: *how can one be sure they are better in a particular case?* So far no equation with universal applicability has been shown. It is conceivable that better equations can be developed by analyzing rooms in more detail (surface size and orientation statistics, absorption and diffusion distribution etc.). However, any such attempt would require a computer model of the room to be made for the analysis and with a computer model of the room the decay can be estimated directly by a CP program using geometrical acoustics (ray-tracing and variants thereof) and a formula is not necessary. Such an estimate requires diffuse reflection to be taken into account in a sufficient manner, a topic to be discussed in Part II.

References, Part I

[Fitzroy-59] "Reverberation formula which seems to be more accurate with nonuniform distribution of absorption," D. Fitzroy, JASA 31, 893-897 (1959)

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[Dalenbäck-94] "A Macroscopic View of Diffuse Reflection," B.-I. Dalenbäck, M. Kleiner, P. Svensson, JAES 42, 973-807 (1994)

[Dalenbäck-95] "The Importance of Diffuse Reflection in Computerized Room Acoustic Prediction and Auralization," B.-I. Dalenbäck, Proc. IOA 17, 24-34 (1995).